

RADIO PULSAR TIMING

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ABSTRACT

The motivation for radio pulsar timing and its basic principles are reviewed. Present and future radio timing techniques and hardware are summarised and compared. The array of present timing programmes and their scientific goals are collated and described. Recent results and future prospects are discussed, with emphasis on multi-wavelength techniques where appropriate. Timing of radio pulsars at other wavelengths is summarised along with the provision of contemporary ephemerides for timing and searches at other wavelengths.

INTRODUCTION: MOTIVATION FOR TIMING

The scope of this paper is confined to timing of rotation powered radio pulsars, as there are many papers in session E1.1 of the COSPAR meeting discussing the timing of accretion powered X-ray pulsars. For this paper, timing will be considered to be semi-regular post-detection measurements of arrival times. In the following two sections, the motivation for radio pulsar timing is discussed in terms of understanding pulsars themselves as well as their use as tools.

Neutron Star Properties, Formation and Evolution

- *Neutron Star Structure:* Pulsars provide an excellent opportunity to study the structure of neutron stars as Alpar has described at this meeting. The steady spin down of some pulsars is interrupted by occasional, sudden increases of rotation rate. These events, known as glitches, have provided strong evidence that neutron stars consist of a solid but brittle crust and a fluid interior. This fluid interior is generally identified with a neutron superfluid. The origins of glitches have been identified with adjustments in ellipticity of the neutron star as it spins down Ruderman 1969 and/or an irregular outflow of angular momentum due to the quantized vortex properties of the interior neutron superfluid Anderson & Itoh 1975.

- *Equations of State:* The properties of neutron stars that can be determined observationally in order to constrain the equation of state are the mass, radius and limiting spin period van Paradijs 1996. Timing measurements shed light on these properties in a number of ways. Measurements of Shapiro delay and other relativistic effects in some cases give very accurate mass determinations Kaspi, Taylor, & Ryba 1994. Masses may also be constrained using radial velocity curves of both pulsars and their optical companions van Kerkwijk, Bergeron, & Kulkarni 1996. In conjunction with ages determined from white dwarf cooling, rotation periods of the fastest millisecond pulsars (MSPs) at birth may be constrained Kulkarni 1992, Bell et al. 1995b. The next generation of surveys (which will be sensitive to periods less than one millisecond) will provide constraints as described by D’Amico in these proceedings.
- *Pulsar Velocities:* The mean birth velocity of normal pulsars (some of which were measured from timing) is 450 km s^{-1} Lyne & Lorimer 1994. These large velocities of normal pulsars have been taken as firm evidence for velocity kicks from asymmetric supernovae. Direct evidence for a substantial birth kick has recently been observed in the precessing binary PSR J0045–7319 Kaspi et al. 1996.
- *Stellar Evolution:* There are several different models for the formation of MSPs and at this stage none can be ruled out Phinney & Kulkarni 1994. Timing is providing clues in unravelling formation history, in terms of velocities Camilo et al. 1997a, Nice & Taylor 1995, accurate positions for studying optical companions Kulkarni 1986, Bell, Bailes, & Bessell 1993, Lundgren, Camilo, & Foster 1996, van Kerkwijk 1996, and eccentricities which provide a useful test of evolutionary models Phinney 1992. Timing of eclipsing millisecond pulsars has provided some very important insights into the nature of their companions and their evolution Stappers et al. 1996, Nice & Thorsett 1996.

Pulsars as Tools

Radio pulsar timing is a field that is interesting not only to study the objects themselves, but also because it is a valuable tool for fundamental tests of physics and many other applications.

- *Tests of Relativity:* The realisation that radio pulsars are superb natural laboratories for testing theories of gravity came with a flurry of publications after the discovery of PSR B1913+16 Hulse & Taylor 1974. Measurement of several relativistic effects allowed a complete solution of the system’s parameters and a self-consistent confirmation of the rate of emission of gravitational waves as predicted by general relativity Taylor & Weisberg 1989. Recently, the fifth relativistic dual-neutron-star binary pulsars was been found Nice, Sayer, & Taylor 1996. When analysed together, these provide even more stringent tests of theories of gravity Taylor et al. 1992. These pulsars have also been used to set limits on variations of the gravitational constant G . The best limit to date is from timing of PSR B1913+16 which gives $\dot{G}/G = 4 \pm 5 \times 10^{-12} \text{ yr}^{-1}$ Taylor 1992, although the limit from PSR B1855+09 should improve on this in the future Kaspi, Taylor, & Ryba 1994. A similar result has been obtained by assuming that present masses of neutron stars reflect the Chandrasekhar mass and thus the value of G when they were formed Thorsett 1996. There is also a range of interesting and useful tests that can be performed using neutron stars in very circular orbits ($e \sim 1 \times 10^{-5}$): tests of the strong equivalence principle Damour & Schäfer 1991, Wex 1996, of local Lorentz invariance Damour & Esposito-Farèse 1992 and of conservation laws Bell & Damour 1996. These latter tests depend linearly on the orbital eccentricity of a sample of binary millisecond pulsars.

- *Interstellar Medium:* Pulsars are excellent tools for studying the interstellar medium (ISM) because they are pulsed point sources. The radio dispersion depends on the column density of free electrons between the pulsar and the observer. Hence measurements of dispersion yield free electron column density estimates for those pulsars which have independently determined distances Lyne, Manchester, & Taylor 1985, Taylor & Cordes 1993. Since the magnetic fields in the ISM lead to Faraday rotation, polarisation studies of linearly polarised pulsars can give estimates of ISM magnetic field strengths Hamilton & Lyne 1988. Scattering on smaller scales leads to rapid variations in the observed flux, called scintillations Rickett 1990. Dispersion measure variation Backer et al. 1993, Kaspi, Taylor, & Ryba 1994 and diffractive scattering Cordes, Pidwerbetsky, & Lovelace 1986 observations provide constraints on the scales of density fluctuations in the ISM and can also be used to determine pulsar velocities Gupta 1995.
- *Time Standards:* Very precise long term timing of PSRs B1937+21 and B1855+09 have demonstrated the long term clock-like stability of MSPs Kaspi, Taylor, & Ryba 1994. Based on this stability, there have been suggestions that MSPs could be used as a new standard of time. Unfortunately, a standard of time based on pulsars would have no link to a reproducible physical phenomenon, whereas the atomic clocks do Bauch 1990. Nevertheless, pulsars such as PSRs B1855+09 and J1713+0747 appear to be more stable on time scales of months to years than atomic clocks. Hence, with enough MSPs well distributed over the celestial sphere, it might be possible to use an ensemble-averaged pulsar time scale as a long term time standard.
- *Reference Frame Ties:* The tying of the radio, optical and planetary reference frames is a difficult proposition. It requires large numbers of randomly distributed sources with accurately determined positions and proper motions in all of the three reference frames. Pulsars provide a good link between the planetary and radio frames as accurate positions can be obtained in each frame. Binary millisecond pulsars are helpful as many have positions and proper motions that will be measurable in all three frames Bell et al. 1995a, Lundgren, Camilo, & Foster 1996. Several VLBI and optical programmes are presently obtaining observations towards this end.
- *Cosmology:* Another novel use of pulsars as tools has been to place limits on the cosmic background of low frequency gravitational waves Romani & Taylor 1983. The best limit is $\Omega_g h^2 < 6 \times 10^{-8}$, from long term timing data on PSR B1855+09, where Ω_g is the fractional energy density in gravitational waves per logarithmic frequency interval and the Hubble constant $H_0 = 100h$ km s⁻¹ Thorsett & Dewey 1996, Kaspi, Taylor, & Ryba 1994. Since such a stochastic background would be produced by cosmic strings, this suggests that cosmic string are rather unlikely to exist Hogan & Rees 1984.
- *Search for Planets:* The discovery of planetary mass companions to a millisecond pulsar Wolszczan & Frail 1992 was unexpected. Their existence has been confirmed by the detection of three-body perturbations in the timing residuals Wolszczan 1994. Naturally, such a discovery creates interest in finding other MSPs with planetary mass companions. Several efforts to search for planets around other pulsars Thorsett & Phillips 1992, Bell et al. 1996, Shemar 1995 have provided only a couple of candidates to date Bailes, Lyne, & Shemar 1993, Backer, Foster, & Sallmen 1993.
- *Solar System Ephemerides:* An accurate ephemeris for the major bodies of the solar system Standish 1990 is vital for transforming topocentric pulse arrival times to barycentric pulse arrival times. The most precisely timed pulsars offer an independent test bed as correlated irregularities in timing data can provide feedback, allowing different ephemerides to be compared and improved Kaspi 1995.

TIMING PRINCIPLES

Measuring Arrival Times

The time-of-arrival (TOA) of a fiducial point in the rotational phase of a pulsar is the fundamental quantity which must be determined. This is normally done by comparison with a standard pulse profile $s(t)$. The observed pulse profile $p(t)$ can be expressed in terms of the standard profile by $p(t) = a + bs(t - \phi) + g(t)$ where a is a DC offset, b is a scale factor, ϕ is a phase shift and $g(t)$ represents noise. For the comparison, full use of the available signal to noise is most easily achieved by cross-correlating the observed and standard profiles in the Fourier domain Taylor 1992. To do this a very accurate time standard is required and is usually obtained from a local hydrogen maser referenced to a standard bank of caesium clocks Bauch 1990.

Transformation to the Pulsar Rest Frame

Having determined the topocentric TOA t , an accurate transformation to the rest frame of the pulsar must be applied. For most single pulsars, a transformation to the barycentre of the solar system is sufficient Backer & Hellings 1986, Taylor & Weisberg 1989. The barycentric time of arrival is

$$t_b = t + \frac{\mathbf{r} \cdot \hat{\mathbf{n}}}{c} + \frac{(\mathbf{r} \cdot \hat{\mathbf{n}})^2 - |\mathbf{r}|^2}{2cd} - \frac{D}{f^2} + \Delta_{E\odot} + \Delta_{S\odot} + \Delta_{A\odot}, \quad (1)$$

where \mathbf{r} is a vector from the barycentre to the phase centre of the telescope, $\hat{\mathbf{n}}$ is a unit vector pointing from the barycentre to the pulsar, c is the speed of light, d is the distance to the pulsar, D is the interstellar dispersion constant, f is the radio frequency, $\Delta_{E\odot}$ is the Einstein delay comprised of the gravitational red shift and time dilation, $\Delta_{S\odot}$ is the Shapiro delay characterising the curvature of space time near the sun and Δ_A is the aberration delay as a result of the Earth's rotation Taylor & Weisberg 1989. Terms two and three together make up the Roemer delay $\Delta_{R\odot}$. The first part of the 3rd term measures the curvature of the wavefronts emitted from the pulsar and can be used to determine a timing parallax for nearby pulsars. The dispersion measure and five astrometric (right ascension, declination, parallax, proper motion in right ascension and declination) pulsar parameters can be determined via this transformation.

High Frequency Timing. At higher frequencies such as infrared, optical, X-ray and gamma rays, dispersive effects are no longer important and $D/f^2 \rightarrow 0$. For ground based optical and infrared observations, the data analysis is therefore considerably simpler. For space or balloon based observations extra transformations (including special relativistic effects) are required to account for the more complicated motion of the observatory. Further, it is not always possible to have a sufficiently accurate clock at the telescope, requiring regular determination of clock offsets.

Binary Pulsars. Further terms are needed to account for binary motion and to obtain the time T in an inertial frame with respect to the pulsar's centre of mass. This transformation is given by

$$t_b = T + \Delta_R + \Delta_E + \Delta_S + \Delta_A \quad (2)$$

where Δ_R , Δ_E and Δ_S are the Roemer, Einstein and Shapiro delays in the binary orbit and Δ_A is the aberration delay as a result of the pulsar's rotation Taylor & Weisberg 1989. The five Keplerian parameters necessary to describe the orbit and account for the Roemer delay are: orbital period, orbital eccentricity, longitude of periastron, epoch of periastron and the projected semi-major axis. A further eight post-Keplerian parameters might be measurable and account for the final three terms in equation 2 Damour & Taylor 1992. In those rare but exciting cases where a pulsar has more than one companion an extra complete set of the four terms Δ_R , Δ_E , Δ_S and Δ_A may be required for each orbit. The above only considers companions that are sufficiently compact to act like point masses, for example neutron stars, white dwarfs and planets. For pulsars with larger or less dense companions, such as PSR J0045–7319 and possibly PSRs J2051–0827 and B1259–63 additional terms are required to account for the quadrupole moment Lai, Bildsten, & Kaspi 1995.

Pulsar Spindown and Dynamics

Having made the above transformations, the pulsar's rotational parameters are now accessible by measuring the rotational phase $\phi(t)$ given by a Taylor expansion

$$\phi(t) = \phi(0) + \nu t + \frac{1}{2}\dot{\nu}t^2 + \frac{1}{6}\ddot{\nu}t^3 + \dots \quad (3)$$

where $\nu \equiv 1/P$ is the rotational frequency, and $\dot{\nu}, \ddot{\nu}$ are the frequency derivatives corresponding to the period derivatives \dot{P}, \ddot{P} . The rotational parameters include a fiducial time defining the phase, the rotation period, and possibly several period derivatives. The values these parameters take are those measured by an observer at infinite distance. To obtain the actual values one must correct for the gravitational redshift of the pulsar. This would typically reduce the value for the period by 30%, however this may vary by a factor of two depending on the equation of state of the neutron star Cook, Shapiro, & Teukolsky 1994. Since the many theoretical equations of state for neutron stars are poorly constrained by observations, such corrections are not normally applied.

As a pulsar may be moving toward or away from the Earth, its measured period will include both the actual period and a contribution from the Doppler effect. While this effect cannot be separately measured, the difference between the measured period and actual period is only 0.1% for a pulsar having a radial velocity of 300 km s⁻¹. The orbital periods of binary pulsars are similarly affected. Pulsars may also have accelerations towards or away from us and the measured period derivatives and orbital period derivatives contain a contribution from the Doppler effect Shklovskii 1970, Damour & Taylor 1991, Camilo, Thorsett, & Kulkarni 1994, Bell & Bailes 1996. Transverse motions can be measured separately from timing Manchester, Taylor, & Van 1974 and indeed transverse velocities for many pulsars have been obtained in this way. While this technique has proved to be difficult for young pulsars due to timing noise Lyne & Smith 1990, more recently the precision with which MSPs can be timed has facilitated proper motion measurements for about half the Galactic population of MSPs Camilo et al. 1997a. Recently the effect of proper motion on the observed semi-major axes of binary pulsars has been shown to be important for fast pulsars in wide face-on binaries Arzoumanian et al. 1996, Kopeikin 1996.

Dispersion Removal

In the pursuit of the highest possible timing precision, the limiting factor is may often be either signal-to-noise or the dispersion smearing of the pulses for those pulsars that do not have significant timing noise Taylor 1996. The need for improved sensitivity inevitably leads to bandwidths as large as possible being used. As a result, the dispersion of the pulses in time across this bandwidth at best leads to broadening of the observed pulse and for fast pulsars, may amount to many pulse periods. Removing the effects of dispersion is therefore of fundamental importance for precise timing and the accuracy with which this can be done limits many of the presently running pulsar timing projects. The properties, advantages and disadvantages of various methods of attacking this problem are summarised in the following list.

- *Filter Banks* offer a relatively cheap and reliable way of removing dispersion and have been used in numerous very functional, productive and scientifically potent timing programmes. In recent times, the the need for very narrow channel bandwidths as well as stable and well-matched gains has exposed the limitations of filter banks for precise timing of MSPs.
- *Correlators* provide the means to overcome these limitations, in particular the gains of the “lags” can be calibrated, giving more timing stability Navarro 1994. However, correlators are substantially more costly and complex to build.
- *Frequency Sweeping* provides a useful method for dispersion removal and is based on a swept local oscillator which closely follows the frequency drift of the pulsar signal McCulloch, Taylor, & Weisberg 1979, Biraud et al. 1989. To date this has not been a widely explored technique and its inflexibility and hardware limitations have made it possible only for intermediate dispersion measures of around $70 \text{ cm}^{-3} \text{ pc}$ at 1400 MHz. However some very precise timing has been achieved Cognard et al. 1993, Cognard et al. 1995.
- *Coherent Dedispersion*, in which the raw base-band signal is recorded prior to square-law detection, after which software transforms are applied to remove dispersion, offers several advantages if the recording system has enough bandwidth to allow sufficiently fast sampling Hankins 1971. The frequency resolution is simply a software parameter so that as new fast computers arrive, the accuracy of the timing experiment can be steadily improved while the costly in-house built hardware of the above methods becomes obsolete Taylor 1996, Hankins, Stinebring, & Rawley 1987, Anderson et al. 1996. Although these ideas have been around for a while, only in the last couple of years have the tape and computing resources become available to make this method feasible for substantial timing projects.
- *Multi-frequency Timing* has demonstrated that dispersion measure variations are one of the more important factors limiting timing precision Backer et al. 1993, Kaspi, Taylor, & Ryba 1994. The path which most groups are now following or are intending to follow is that of simultaneous timing at two or more frequencies. This allows the dispersion measure variations to be determined so that appropriate corrections to timing parameters can be made Kaspi, Taylor, & Ryba 1994.

TIMING PROGRAMMES

In this section some of the large and long term timing programmes and their recent results are summarised. A more complete table of timing programmes, principle contacts, sources lists and observation intervals can be found on the WWW (<http://astro.berkeley.edu/~mpulsar/>).

Millisecond Pulsars

Using Arecibo, the Princeton group has set the standard of precision timing, starting with the millisecond pulsars B1937+21, B1855+09 Kaspi, Taylor, & Ryba 1994 and also J1713+0747 Camilo, Foster, & Wolszczan 1994. At 1400 MHz, the rms residuals for two of these pulsars are at the $0.3\mu\text{s}$ level. There are now 14 MSPs in the timing list, observed at roughly fortnightly intervals (except while the present Arecibo upgrade is taking place). Eight other MSPs are also being timed at the VLA by the Princeton group. The Penn State group, also using Arecibo, have confirmed the very exciting planets around PSR B1257+12 Wolszczan 1994. Using the 42m and 25m at Green bank, the Berkeley group has conducted multi-frequency timing of 15 MSPs, some for up to six years, and has produced some useful results including detailed studies of dispersion measure variations Backer et al. 1993, Backer & Wong 1996 and independent confirmation of the planets around PSR B1257+12 Backer, Sallmen, & Foster 1992.

The Nançay group has achieved some impressive results, timing PSR B1821–24 and PSR B1937+21 since 1988, achieving rms timing residuals of $0.3\mu\text{s}$ for PSR B1937+21 Cognard et al. 1993, Cognard et al. 1995. The Parkes and Jodrell groups have been timing all MSPs including those in globular clusters, since their discovery. The highest levels of precision have not yet been achieved since to a large degree the observed profiles are dominated by dispersion smearing Bell et al. 1996, Camilo et al. 1997a. The rms residuals are steadily improving, particularly with the vastly improved frequency resolution afforded by the Caltech correlator Navarro 1994, Sandhu et al. 1996 at Parkes and the new timing machine at Jodrell. Some interesting results have been obtained with high frequency timing at Effelsberg, including pulse shape variations of PSR J1022+1001 Camilo et al. 1997b.

High Mass Binary Pulsars

The two groups of pulsars categorised as high mass binaries are the dual-neutron-star binaries such as PSR B1913+16 and those with high mass young stellar companions, PSR B1259–63 and PSR J0045–7319. The known dual-neutron-star binaries are all in the northern hemisphere and the long term timing programme of the Princeton group has produced the most results, including confirmation of the predictions of general relativity at better than the 1% level Damour & Taylor 1991, Taylor et al. 1992. At its last periastron passage in January 1994, PSR B1259–63 revealed some remarkable interactions with its Be star companion, including the disappearance of the pulsar, huge dispersion measure and rotation measure variations and a continuum source possibly due to a wind interaction or jet Johnston et al. 1996, Johnston 1996. Recent X-ray observations Kaspi et al. 1995, Kaspi 1996 are more easily explained by the wind interaction model Tavani, Arons, & Kaspi 1994. PSR J0045–7319 is a binary system with a B star and shows no frequency dependent variations of any kind Kaspi, Tauris, &

Manchester 1996. However the orbital plane has recently been shown to be inclined to the rotational axis of the B star, giving rise to spin-orbit coupling and precession of the pulsar orbit Kaspi et al. 1996. This has provided independent evidence for a substantial neutron star birth kick.

Glitching Pulsars

Long-term regular monitoring of old favourites including the Crab and Vela has been continued by most groups and several new glitches have been observed Lyne, Pritchard, & Smith 1993, Arzoumanian 1995 including a giant glitch in PSR B1757–24 Lyne et al. 1996a. Some groups continue to monitor individual pulsars such as Vela for up to 18 hours per day McCulloch 1996. A large number of young pulsars were found in high-frequency Galactic plane surveys Clifton & Lyne 1986, Johnston et al. 1992 and the timing of these and other pulsars has resulted in the discovery of over 25 glitches Shemar & Lyne 1996. This large number of glitches, now 50 in total, has allowed statistical studies which indicate that post-glitch relaxations can be separated into two exponential components for most pulsars Shemar, Lyne, & Smith 1996. Alpar (this meeting) has shown that the majority of glitches are inconsistent with the crust cracking model, but are explained by the superfluid vortex pinning model. Recently the long time span of data on Vela has been collated and used to demonstrate that its braking index is 1.4 ± 0.2 Lyne et al. 1996b which is impressive given the frequency and magnitude of its glitches.

Timing at Other Wavelengths

Radio pulsar timing at wavelengths other than radio until recent times has been mostly restricted to two pulsars, the Crab and PSR B0540–69 at optical wavelengths, although there was also some timing of Vela Manchester et al. 1980. Caraveo and others (this proceedings) give more detailed discussions of timing at these wavelengths. There was extensive optical timing of the Crab pulsar during the 1970's Lohsen 1981 which resulted in the detection of glitches Lohsen 1975, Groth 1975 and also studies of the random walk nature of timing noise Cordes 1980. Recently there have been simultaneous timing studies of the radio giant pulses and gamma-ray pulsations Lundgren et al. 1995. PSR B0540–69 was discovered in X-rays Seward, Harnden, & Helfand 1984 but most of the timing, including measurement of the braking index has been at optical wavelengths Middleditch, Pennypacker, & Burns 1987, Manchester & Peterson 1989, Gouiffes, Finley, & Ögelman 1992, Boyd et al. 1995. It was eventually detected in the radio after some very long integrations by radio search standards Manchester et al. 1993. Recently braking indices for the Crab and PSRs B0540–69 and B1509–58 have been determined from X-ray timing observations using Ginga Nagase et al. 1990. The gamma-ray pulsar Geminga has not been detected at radio wavelengths but is mentioned here due to its similarity to Vela and other radio pulsars. There has been a considerable amount of timing of Geminga, in particular using COS B Bignami & Caraveo 1992, Grenier et al. 1994 and SAS 2 Mattox et al. 1992 which accumulated over 10 years of timing data.

Contemporary Ephemerides. A fundamental reason for the provision of contemporary ephemerides for timing and searches at other wavelengths is that in many cases, less than one photon per pulse period is observed. For example the average separation between photons from the Crab when observed by EGRET is 10 minutes, which corresponds to about 18000 pulse periods Thompson 1993. The resulting long

integration times may lead to pulse smearing if period derivatives and binary motion are not accounted for. Another important reason is that a 3 sigma event is only a detection if the search parameter space is small and if the noise is normally distributed. If a range of frequencies in a power spectrum must be searched then the significance level of a peak of power P is $S = (1 - e^{-P})^N$, where N is the number of frequencies searched Press et al. 1992. If N is large, S very quickly becomes a small number, unless P is also large. Further, noise in a power spectrum is exponentially distributed, not normally distributed. However, if the data can be folded according to an accurate ephemeris, much weaker signals can be reliably detected.

Present Arrangements. Previously, most of the distribution of up-to-date ephemerides has been by personal contact, often via the Princeton email exploder (psrtime@pulsar.princeton.edu). There have of course been some pulsars for which more organised processes have been established such as the GRO database provided by Jodrell Bank, Parkes and Princeton which is maintained at Princeton (ftp pulsar.princeton.edu). Another example is the Crab pulsar ephemerides Lyne, Pritchard, & Smith 1993 which have been available for the past 12 years and have been on the WWW (<http://www.jb.man.ac.uk/~pulsar/>) for a while.

Future Possibilities. The Princeton group provide a WWW search facility (<http://pulsar.princeton.edu/>) through which pulsar parameters can be readily obtained. This server has provided a good prototype, offering rapid, simple access to many pulsars. The Jodrell Bank group will shortly be providing a similar but vastly more extensive database, containing up-to-date ephemerides for every pulsar observable from Jodrell, ie, parameters for over 300 pulsars (<http://www.jb.man.ac.uk/~pulsar/>). Hopefully other groups with regular timing programmes will provide similar access in the future.

FUTURE PROSPECTS

In this section, some of the areas in which substantial progress is likely to be made in the next few years are noted. A large fraction of these relate to MSPs, as most of them have only recently been discovered and many new effects are now accessible due to the high timing precision attainable.

Timing Noise and Time Standards

An enormous timing database (equivalent to over 3000 years of data on a single pulsar) has been collected at Jodrell Bank and is presently being analysed Martin, Lyne, & Pritchard 1997. This will allow a very complete understanding of timing noise and improve on previous studies Arzoumanian 1995. The time span of data collected for a number of MSPs will soon be long enough to assess the extent to which timing noise also occurs for the fastest pulsars Taylor 1996. In this respect the next few years should establish whether or not pulsars can really be used as long term standards of time.

Dynamical Effects

It should be possible to improve distance estimates to MSPs not only using interferometric techniques, but also by measuring timing parallaxes Ryba & Taylor 1991, Camilo, Foster, & Wolszczan 1994, Sandhu

et al. 1996 and orbital period derivatives Bell & Bailes 1996. If accurate distances to some high Galactic latitude binary MSPs can be obtained, it may be possible to constrain dark matter in the local Galactic disk Bell & Bailes 1996. Many more proper motions should be measurable Camilo et al. 1997a and when combined with accurate distances, will allow intrinsic period derivatives to be determined Camilo, Thorsett, & Kulkarni 1994, Shklovskii 1970. Useful constraints on orbital inclinations may come from measurements of the proper motion contribution to the apparent semi-major axis Kopeikin 1996, while pulsar orbital parallaxes Kopeikin 1995 may require more substantial improves in timing precision. As the timing residuals reduce for many of the more recently discovered MSPs, there are likely to be a few more for which Shapiro delay can be measured, providing constraints on companion masses.

Tests of Relativity

Important progress is likely to be made in constraining theories of gravity by combining the results from several dual-neutron star binaries Taylor et al. 1992, Damour & Taylor 1992, although nearby objects will need interferometric distances Bell & Bailes 1996 if they are to live up to their full potential Arzoumanian 1995. For the other tests and for limits on \dot{G} and ultra-low-frequency gravitational waves (mentioned in the introduction), small improvements will come with continued observations. Substantial improvements will require the discovery of new more extreme systems, novel methods and new effects. There are several gravitational lensing effects that occur if a binary pulsar orbit is sufficiently edge on Schneider 1989, Schneider 1990, Doroshenko & Kopeikin 1995 that are presently extremely difficult to measure.

Speculation

If the polarisation of MSPs can be understood, it may be possible to determine the inclination of the spin axes and therefore the orbits (if the angular momenta are assumed to be aligned). While the lack of short orbital period planets around MSPs seems to be established at this time Bell et al. 1996, the existence of planets like those in the outer solar system will be tested over the next few years. The next generation of telescopes such as a square kilometer array offer many exciting prospects for pulsar timing. The discovery of novel effects and new types of systems such as black hole pulsar binaries is also possible.

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